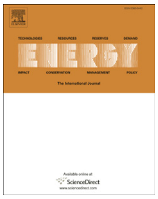
Energy xxx (2015) 1–16

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Higher renewable energy integration into the existing energy system of Finland – Is there any maximum limit?

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A R T I C L E I N F O

Article history:
Received 3 November 2014
Received in revised form
2 January 2015
Accepted 4 January 2015
Available online xxx

Keywords:
Energy system modeling
Energy planning
Renewable energy integration
Techno-economic optimization
Wind integration
Heat pump

A B S T R A C T

Finland is to increase the share of RES (renewable energy sources) up to 38% in final energy consumption by 2020. While benefiting from local biomass resources Finnish energy system is deemed to achieve this goal, increasing the share of other intermittent renewables is under development, namely wind power and solar energy. Yet the maximum flexibility of the existing energy system in integration of renewable energy is not investigated, which is an important step before undertaking new renewable energy obligations. This study aims at filling this gap by hourly analysis and comprehensive modeling of the energy system including electricity, heat, and transportation, by employing EnergyPLAN tool. Focusing on technical and economic implications, we assess the maximum potential of different RESs separately (including bioenergy, hydropower, wind power, solar heating and PV, and heat pumps), as well as an optimal mix of different technologies. Furthermore, we propose a new index for assessing the maximum flexibility of energy systems in absorbing variable renewable energy. The results demonstrate that wind energy can be harvested at maximum levels of 18–19% of annual power demand (approx. 16 TWh/a), without major enhancements in the flexibility of energy infrastructure. With today's energy demand, the maximum feasible renewable energy for Finland is around 44–50% by an optimal mix of different technologies, which promises 35% reduction in carbon emissions from 2012's level. Moreover, Finnish energy system is flexible to augment the share of renewables in gross electricity consumption up to 69–72%, at maximum. Higher shares of RES calls for lower energy consumption (energy efficiency) and more flexibility in balancing energy supply and consumption (e.g. by energy storage).

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1. Introduction

The confluence of climate change mitigation, security of energy supply, and promotion of distributed generation has stimulated national energy policies towards higher integration of RES (renewable energy sources). The EU energy targets aim to reduce the greenhouse gas emissions by over 80% by 2050, compared to 1990 levels [1]. This necessitates more efforts across the EU to augment the share of RES in final energy consumption by 30% and RES-E (renewable-based electricity) up to 50% by the year 2050 [2].

Finland is one of the successful EU States on the path in meeting 2020's energy targets [3], with over 30% RES in final energy consumption in 2012 [4]. The recent update of Finland's Energy and Environmental Policy [5] underlines fossil fuel consumption and power imports as two events that should be alleviated with new decarbonized energy production, e.g. by employing nuclear power, wind power, and more bioenergy. While Finland is committed to maintain 38% RES in final energy use by 2020, further increase in the share of RES beyond this target has attracted a wide attention in common energy debate. In other words, it is not evident for the policy makers and energy experts that what limits of RES are achievable and what techno-economic implications await the whole energy system under higher levels of RES integration. These salient questions should be properly answered when undertaking a new commitment to the EU or planning national RES-based energy scenarios.

The large-scale integration of RES in energy systems has long been subject to a wide range of researches, e.g. Refs. [6,7]. Other studies have further analyzed the case of 100% RES in electricity production, e.g. in Australia [8], Japan [9], New Zealand [10], as well as storage demand for 100% RES electricity in a global scale [11]. Considering the whole energy system, Ref. [12] examines the case of high-RES for Germany, Ref. [13] highlights the role of energy storage in a 100% RES Europe, whereas Refs. [14] and [15] postulate

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Abbreviations: CHP, combined heat and power; CEEP, critical excess electricity production; DH, district heating; HDD, heating degree days; HP, heat pump; MREI, maximum renewable energy index; NPE, net power exchange; PEC, primary energy consumption; PFC, primary fuel consumption; RES, renewable energy source; RES-E, renewable-based electricity; VTT, Technical Research Center of Finland.

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http://dx.doi.org/10.1016/j.energy.2015.01.007
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a roadmap towards 100% RES by 2050 for Denmark and Macedonia, respectively. The results of these contributions typically call for structural changes in the energy system; such as electrification of heat sector and transportation, employment of innovative technologies for large-scale energy storage, establishment of power-to-gas supply chain in energy infrastructure, and adoption of supportive regulations for diffusing the mentioned solutions. While the technical feasibility of such structural changes should be thoroughly examined, the economic consequences for achieving such ambitious plans are also unavoidable questions to be addressed. The other quintessential outcome of these researches is the necessity of studying the "flexibility" based on the particular characteristics of each energy system, including demand regime, available resources, existing infrastructure, and the possible interconnection of heat, power, and transport sector. The term "flexibility" is used to assess the capability of an energy system to encounter with variation and uncertainty in both load and generation [16].

The integration of higher shares of RES in Finland's energy system has been subject for research in a number of contributions. Lund [17] and Niemi et al. [18] have investigated the possibility of increasing wind power in Helsinki region by analyzing spatial aspects and multi-carrier energy flows. Other studies have also examined the role of RES in Finland's energy system from policy and dependency viewpoint [19,20], rather focusing on detailed technical consequences. In a study [21] by VTT, Technical Research Center of Finland, a number of low-carbon scenarios are developed based on radical technological changes as well as non-technical (behavioral and consumption-related) recommendations. Finnish Energy Industry [22] has also outlined a future low carbon by emphasizing the role of electrification and district energy systems. In this study, however, we aim at portraying the maximum flexibility of the existing energy system in integration of RES with addressing both technical and economic implications in national level. By exploring the flexibility of the existing energy system, we are to establish a signpost for energy experts and policy makers to build their future high-RES scenarios on a more realistic basis.

To this end, by applying hourly analysis, the Finnish energy system is modeled in an integrated manner (heat, power, industry, and transport sectors) for the year 2012 as a reference model. Next, the increase in the share of RES is investigated by exploring the maximum potential of different technologies including bioenergy, hydropower, solar energy, wind power, and individual HPs (heat pumps). Finally, a combination of different RES systems that promises the highest RES in final energy consumption is realized. The remaining of this contribution is structured as follows. The methodology applied in this study is described in Section 2. A new indicator for assessing the maximum RES integration is proposed in this Section. The current situation of Finnish energy system is briefly reviewed in Section 3 and resource potential of different RES technologies is discussed. The results are presented and discussed in Section 4, followed by conclusions in Section 5. Solar cooling and concentrated solar thermal are not addressed in this analysis, as well as other RES technologies such as tidal, wave, and geothermal.

2. Methodology

2.1. Modeling of national-level energy systems

Different studies have highlighted the main challenges in modeling of energy systems bundled with recommendations for future developments [23,24]. Pfenninger et al. [25] categorizes national energy models as energy system optimization models, energy system simulation models, power system and electricity market models, and qualitative and mixed-method models. As suggested by Dodds et al. [26], the characteristics that distinguish energy system models from each other can be sorted as the model's paradigm and equations, locational and temporal dimensions, model's structure or topology, model's constraints and boundaries, and required parametric data. While some models suggest energy planning based on some selective operational occasions in the system, like summer and winter peaks, other models examine more temporal details. For example, an hourly-based energy system analysis offers more capabilities in illustrating the fluctuating nature of RES-based energy scenarios, where the corresponding data is available [27]. Furthermore, hourly resolution in energy system modeling offers opportunities in capturing the hourly variability of the heat and power demands, as well as power exchanges based on hourly electricity prices available. Despite the fact that collecting sub-hour data for energy system modeling is rather difficult and complex, it has been shown that modeling with resolutions of 5 min improves the results of hourly analysis just by 1%, in terms of yearly costs and benefits [28]. While detailed comparison of different energy models is beyond the scope of this study, based on the review of different energy system modeling tools [29–31], the authors recognized EnergyPLAN as a suitable tool for the scope and details of this analysis.

EnergyPLAN [32] is a deterministic model capable for hourly analysis of nation-wide energy systems by offering various options for integration of different RES systems. Since EnergyPLAN is applicable for the energy systems with high shares of CHP [33] interlinked with high shares of variable RES [6,34], and possibility to convert power into different energy carriers, it was selected for the purpose of this study. EnergyPLAN has already been employed for the modeling of RES integration into different national and regional energy systems, including Ireland [35], China [36], the province of Ontario, Canada [37], the UK [38], and other countries and regions (e.g. Refs. [39–46]). More information about the tool, its structure, documentation, case studies, and built models can be seen in Ref. [32].

2.2. The maximum limit for integration of variable RES

As the integration of variable RES is still in its primary stages in many countries, defining an upper limit for the share of variable RES is not so relevant either widely discussed in the literature. However, in RES-based energy planning and modeling of large-scale variable RES (e.g. in wind integration studies), the maximum integration level of variable RES into an energy system should be addressed by a proper criterion. From energy system viewpoint, the magnitude, duration, frequency, and time of occurrence of such fluctuations are important for calculating required flexibility solutions, like power ramping and/or energy storage. In other words, a proper measurement index is required to quantify under which occasion higher variable RES is undesirable, costly, and problematic for the energy system.

Different studies have proposed metrics for the assessment of the flexibility of power systems, e.g. see Refs. [47,48]. Ma et al. [16] defines a flexibility index by evaluating and aggregating the ramping rate of generation fleet considering their scheduled generation. Lannoye et al. [49] calculates the net load ramps by investigating ramping availability of individual plants in different time horizons. The mentioned methods require rather detailed information about different individual plants and their functional capabilities in different conditions. From energy system perspective, Lund [50] suggests the term CEEP (critical excess electricity production), expressed in TWh/a, for those levels of wind production that cannot be integrated in domestic energy system, cannot be stored or converted to other energy carriers, and are beyond the cross-border transmission capacity. In addition to the magnitude, Hedegaard and Meibom [51] examine the issue of wind oversupply in different time scales, from hourly to daily and longer periods.

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Connolly et al. [35] proposes a COMP (compromise coefficient) to reflect the conservation in PEC (primary energy consumption) due to further integration of variable RES. The latter argue that if marginal reductions in PEC in two consecutive wind integration levels would be higher than annual excess power caused by wind, it is still feasible to consider that level of wind integration.

In this study, we propose a more realistic indicator to examine the maximum level that variable RES can be integrated into an energy system. Since most of the national-level energy systems are nowadays connected to external electricity markets, the impact of RES integration on NPE (net power exchange) should not be overlooked. In other words, the high-level integration of variable RES will reduce power imports (or increases power exports), resulting in higher self-sufficiency of the energy system. Hence, the authors define the indicator of MREI (Maximum Renewable Energy Integration), explained in Eq. (1), to address the consequences of excess power production caused by variable RES with regard to the effect of variable RES on both PEC and cross-border power exchange:

$$\begin{aligned} MREI &= \frac{total\ benefits\ of\ added\ RES}{total\ production\ of\ added\ RES} \\ &= \frac{\Delta NPE + \Delta PFC}{\Delta RES} \quad \left[\frac{TWh/a}{TWh/a}\right] \end{aligned} \tag{1}$$

The symbol Δ denotes the changes between two levels of variable RES integration. In Eq. (1), ΔRES stands for the incremental increase in variable RES production including the excess power that is beyond the flexibility of the energy system. ΔPFC denotes the reduction in primary fuel consumption including biomass resources,[1] so negative values are not desirable. To calculate the changes in net power exchange (ΔNPE), the reduction in power imports (or increase in power exports) is considered a positive event and inserted by (+) sign. This way, a negative ΔNPE denotes higher electricity imports (or lower power exports), which is not desirable. The authors considered $MREI \geq 1$ as acceptable events in RES integration[2] with the lower limit of $MREI = 1$ for the maximum RES integration. It means the addition of new installations of variable RES can be accepted by the system, if the corresponding produced power (including excess, unused power) would result in improving the power exchange in external power market, as well as reducing primary fuel consumption. The functionality of this index is illustrated in Section 4.4.2 (more details in Table B.1 in Appendix B) for the case of wind integration.

2.3. Reference model for Finnish energy system

A reference case for Finland is modeled for the year 2012 based on the available data and official statistics. Fig. 1 portrays the schematic outline of the algorithm applied in this study to model the energy system, by the aid of EnergyPLAN modeling tool.[3] The approach is based on the market-economic optimization, which implies that all the power producers in the market seek to optimize their profits so that the whole energy system would function with the least possible costs. The effect of employing different power production technologies on the market prices is also taken into account through a price elasticity function expressed in Eq. (2), by which market price (P_m), system price (P_s), basic price (P_o), and price elasticity factor (e_p) are related to the net amount of power imports (Q_{net}).

$$P_m = P_s + \left(\frac{P_s}{P_o}\right) * e_p * Q_{net} \quad [€/MWh] \tag{2}$$

In summary, for each particular hour throughout the year, the power demand is first met by nuclear baseload, run-of-the-river hydro, non-adjustable distributed generation, inflexible production of power in industry, and other must-run power plants. Simultaneously, heat demand is partly fulfilled by heat generation at households (including individual HPs, electric heating, and boilers) and distributed heat generators. Then, the annual amount of heat demand in DH (district heating) networks is determined for each hour (see Section 2.3.1 for more details). For DH networks, CHP plants in addition to heat-only boilers supply the heat demand. Consequently, the corresponding power produced in CHP plants feeds the power grid. After this step, the energy system exchanges power with external power market, based on a market-economic optimization scheme. Each block of power capacity is introduced to the market based on the marginal production cost of technologies (merit order). This new capacity will be settled if and only if the marginal cost of production would be lower than the governing market price after the addition of this capacity, considering fixed transmission capacity to the external market and market's price elasticity (see Eq. (2)). The external power market is modeled based on the Nash–Cournot assumption implying no changes in power supply by other producers (even in other countries connected to the market). After reaching the bottleneck, the deficiency in power supply is compensated with domestic condensing thermal power plants, demand side management, and peak and reserve plants if needed. Power oversupply from variable RES undergoes the flexibility steps explained in Section 4.4.2 so that the maximum possible amount of RES-E could be dispatched to the system. Finally, power demand is balanced and the remaining RES-E, if any, has to be curtailed (impossible to use, export, displace, or convert to heat). For more details concerning the problem formulation see the documentation of EnergyPLAN tool, Chapter 6 in version 11.1, freely available in Ref. [32].

Concerning the limitations of the proposed model, it does not present intra-hour behavior of production modes, e.g. ramping constraints, and stand-by/shut-down/start-up costs of the thermal power plants. The model is deterministic, thus by nature it does not capture the uncertainties in modeling of high wind and high solar scenarios. Regarding solar energy, the data of radiation are taken from two cities (Helsinki and Tampere) and generalized to the whole country that might be far from the real distribution of solar uptake over the entire country. The applied methodology does not cover the spatial limitations and power grid transmission constraints, implying that power network can handle the intermittency and variations of proposed wind integration levels.

2.3.1. Input data and assumptions

To construct the energy system model, first, the hourly distribution of power demand and market prices of electricity for the reference year (2012) are obtained from Ref. [52]. Then, the capacity of the Finnish energy system for power and heat production is quantified based on Statistics Finland [4], e.g. see the power capacity in peak load in Table 1.

Finnish energy system is assumed to be connected to one price area (Nordic electricity market) with one transmission corridor, while in reality Finland can exchange power with Estonia as well as importing electricity from Russia. The authors admit that this approach can affect the amount of temporal export and import (up to 8% relative difference), yet the amount of net power imports in the results shows an acceptable deviation from the recorded data (less than 1%).

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[1] It does not include secondary fuels from non-biomass-based RESs, like hydrogen or synthetic gas from wind power.

[2] The choice of limit for MREI can be selected differently based on the research questions for other studies.

[3] It should be noted that this algorithm is one of the possible optimization alternatives included in EnergyPLAN tool, given that the tool can be tailored and customized based on each case study.

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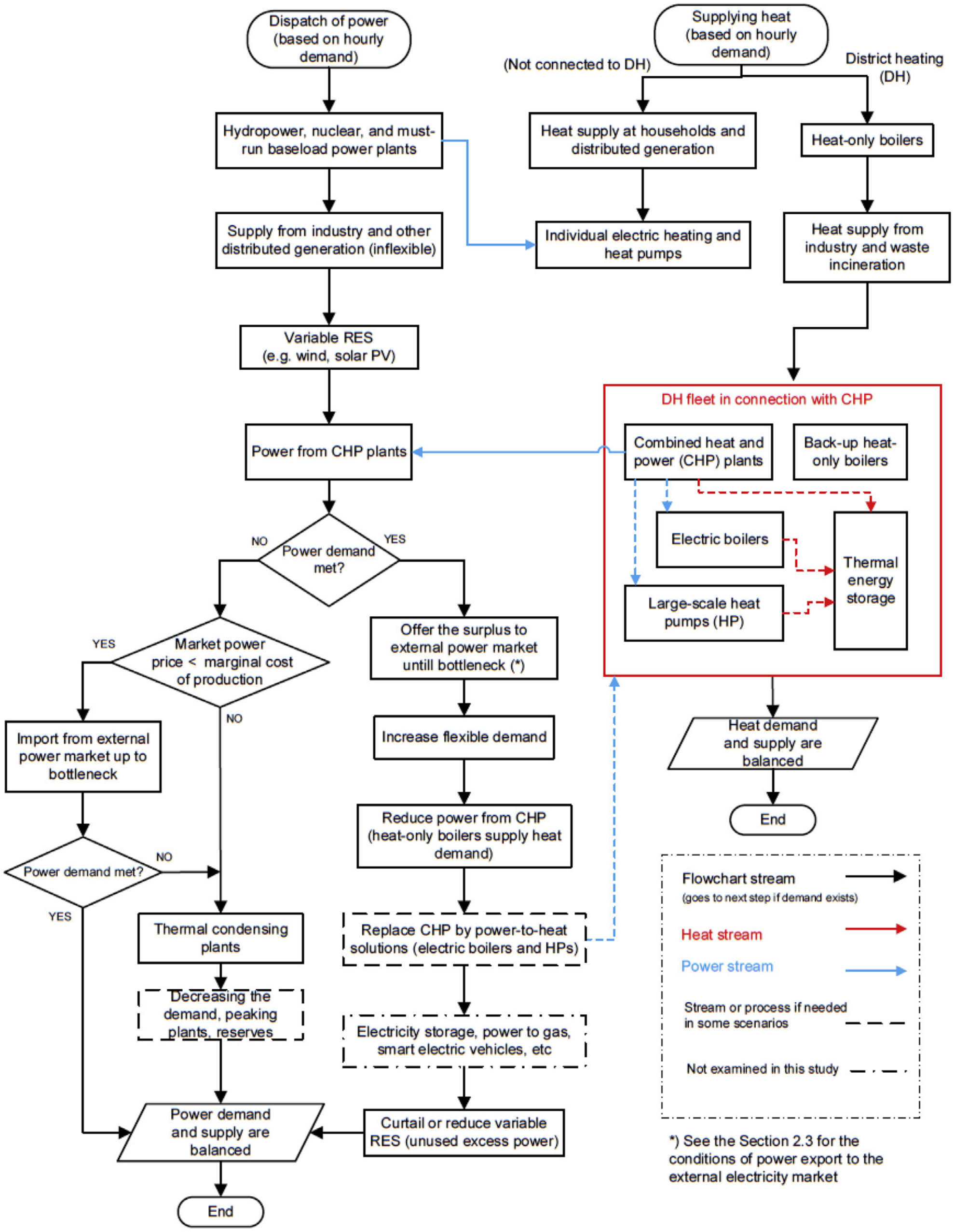
Dispatch of power (based on hourly demand)
Hydropower, nuclear, and must-run baseload power plants
Supply from industry and other distributed generation (inflexible)
Variable RES (e.g. wind, solar PV)
Power from CHP plants
Power demand met?
NO
YES
Market power price < marginal cost of production
YES
NO
Import from external power market up to bottleneck
Power demand met?
NO
YES
Thermal condensing plants
Decreasing the demand, peaking plants, reserves
Power demand and supply are balanced
End
Offer the surplus to external power market untill bottleneck (*)
Increase flexible demand
Reduce power from CHP (heat-only boilers supply heat demand)
Replace CHP by power-to-heat solutions (electric boilers and HPs)
Electricity storage, power to gas, smart electric vehicles, etc
Curtail or reduce variable RES (unused excess power)
Supplying heat (based on hourly demand)
(Not connected to DH)
District heating (DH)
Heat supply at households and distributed generation
Individual electric heating and heat pumps
Heat-only boilers
Heat supply from industry and waste incineration
DH fleet in connection with CHP
Combined heat and power (CHP) plants
Back-up heat-only boilers
Electric boilers
Large-scale heat pumps (HP)
Thermal energy storage
Heat demand and supply are balanced
End
Flowchart stream
(goes to next step if demand exists)
Heat stream
Power stream
Stream or process if needed in some scenarios
Not examined in this study
*) See the Section 2.3 for the conditions of power export to the external electricity market

Fig. 1. Schematic flowchart of the methodology applied in this study to supply power and heat in an integrated way based on hourly time series of power and DH (district heating) demand, variations of RESs, and market prices of electricity.

The capacity of CHP plants in DH and industrial sectors are specified for the model with their fuel mix. In order to define the heat demand, the concept of HDD (heating degree days) is applied. Based on the guidelines provided by Finnish Meteorological Institute [53], the heat demand is calculated for indoor comfort temperature of 17 °C, assuming no need for heating in spring when outdoor temperature crosses 10 °C, while heating is started in autumn when ambient temperature falls below 12 °C (see Appendix A). The HDD are determined based on the hourly averaged ambient temperatures obtained for a weather station in Central Finland. This method is an approximation, as heat demand trend is not identical in different regions or different buildings in a rather large country like Finland. Moreover, the share of DH network in heat supply fleet is not uniform across different regions in the country as we modeled in this study. However, incorporating different energy sectors of a country in one model requires some levels of approximation and generalization.

The investment cost, fixed O&M, and variable costs of technologies are mainly based on [54–58], while fuel costs and taxes from Ref. [59] (see Appendix A). Average carbon price of 8 €/tonne in 2012 is considered for the general calculations, otherwise mentioned. The main input data regarding heat and power demand and supply in industry sector, households, and transport sector are obtained from Statistics Finland [4] and Finnish Energy Industries [60].

2.3.2. Validation of the model

In another contribution [61], the authors have compared the reference model in EnergyPLAN for the Finland's energy system with recorded data for the year 2012. Yearly results show an error of less than 1% for domestic production modes and net power

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Table 1
Domestic power generation capacity in Finland at peak load in 2012 (Statistics Finland [4]).

Power production mode	Power capacity (MWe)	Share %
Nuclear power	2750	19.6
Hydropower	2595	20.8
Condensing power plants	2045	15.4
CHP industry	2370	17.9
CHP-DH	3490	26.3
CHP, total	5860	44.2
Total	13,250	100

imports. The other examined output is the consumption of different fuels and corresponding carbon emissions. By excluding energy gained from ambient air for heat pumps, recycled fuels, and heat of industrial reactions, total energy consumption stagnates at 368.6 TWh for Finland in 2012, based on [4]. The results of our reference model suggest the total energy consumption of 369.9 TWh and emissions of 47.6 Mt CO_2, indicating relative errors of 0.33% and 2.15%, correspondingly. Table 2 compares the results calculated by the reference model in this analysis and the recorded data for 2012, obtained from Statistics Finland [4]. The emission factors of oil and coal (simulated together with peat) are calculated based on the share of different compounds. For example, oil in Table 2 comprises of 22% motor gasoline, 30% diesel fuel, 22% light fuel oil, 11% heavy fuel oil, 4% LPG and 11% other oil refinery compounds [4]. The results of the reference model EnergyPLAN for monthly results show a higher error, lower than 6% on average. Based on the comparisons, it is concluded that the reference model has properly captured the details of the Finnish energy system for the purposes of this study.

3. Case study: Finland's energy system

3.1. Energy mix in Finland

According to Statistics Finland [4], PEC in Finland reached to 381 TWh in 2012, which was 2% less than 2011. The use of renewable energy sources increased by 5% and reached to 30% of PEC. Carbon emissions totaled 46.6 Mt, which was the lowest since 1990. In Fig. 2, the share of different energy sources in PEC in Finland is illustrated for the year 2012, based on data from Ref. [4]. Power demand was 85.1 TWh in 2012, of which 20% was imported. The production of hydropower and wind power was 16.7 and 0.5 TWh, respectively. Nuclear power is responsible for one-third of country's electricity production. Approximately, 27% of total electricity consumption was supplied by CHP production. The production of district heat was 37 TWh in 2012, with a typical cold winter. CHP plants were producer of 70% of DH demand, using 59.2 TWh fuels in cogeneration, from which 25% was biomass. The energy use in industry totaled 150 TWh, with forest industry responsible for 55% energy use in industry sector. The final energy consumption in transport sector was 16% of national energy use (49.9 TWh), of which the share of biofuels was 2.5 TWh.

3.2. RES (Renewable energy sources) in Finland

3.2.1. Bioenergy

Finland is one of the leading countries in biomass use for energy production. Bioenergy accounts for approximately 25% of total energy consumption, 92 TWh in 2012, considered as the backbone of fuel consumption in Finland's future RES scenarios. Since 80% of wood-based bioenergy is produced and consumed in forest industry, the future of bioenergy in Finland is highly correlated to the status of forest-based industries and the use of forest-based biomass [62]. Forest chips (harvesting residues, stumps, and small-diameter energy wood), biogas from biowaste and energy crops, and second generation biofuels (derived from woody biomass) are emphasized as major potential resources for growth in bioenergy use in the future. Based on Finnish Forest Research Institute (Metla), the use of forest chips in heat and power production totaled 16.6 TWh in 2012 [63]. The Ministry of Employment and Economy has defined the target of 25 TWh for forest chips as fuel for heat and power production by 2020, which shows the highest increase among different biomass resources in that scenario [64].

The estimation of biomass potential is a challenging task, as different studies apply different geographical focuses, methodologies, constraints, scenario assumptions, and biomass categories. Different studies have addressed the potential of forest-based bioenergy in Finland, e.g. Ref. [65]. In Ref. [66], it is estimated that Finland has mobilized only 14% of its potential forest chips, and Sikkema et al. [67] demonstrate a potential of 105 TWh for bioenergy from Finnish forests, under current sustainability specification scheme. Concerning forest chips, 50–70% of the theoretical potential can be mobilized, based on Verkerk et al. [68]. Peltola and Ihalainen [69] state the maximum sustainable potential of 25 Mm^3 (51 TWh) for forest chips in Finland. Kärhä et al. [70] also estimates the techno-ecological potential of forest chips in the range of 43–50 TWh, while techno-economic potential of 27–29 TWh. The theoretical potentials can be moderated with advanced assessment

Table 2
Total energy consumption and carbon emissions in Finland 2012, calculated by the reference model in this analysis compared to the statistics from Finnish authorities.

Energy source	Annual consumption (TWh), 2012		Difference	Error
	This study by EnergyPLAN	Statistics Finland [4]		
Coal	51.77	34.76	−1.05	1.98%
Peat		18.06		
Oil	91.84	90.25	1.59	1.76%
Natural gas	31.34	31.95	−0.61	1.89%
Biomass	93.34	92.10	1.24	1.35%
Nuclear	66.84	66.86	−0.02	0.03%
Hydro	16.67	16.67	0.00	0.00%
Wind	0.49	0.49	0.00	0.00%
Total domestic[a]	352.39	351.13	1.16	0.36%
Net power import	17.46	17.44	0.02	0.11%
Total energy consumption[a]	369.85	368.57	1.18	0.33%
CO_2 emissions (Mt)	47.60	46.60	0.97	2.15%

[a] Excluding the segment “Others” in Finnish statistics, which comprises ambient heat, reaction heat, and recycled fuels (totaled 12.42 TWh in 2012).

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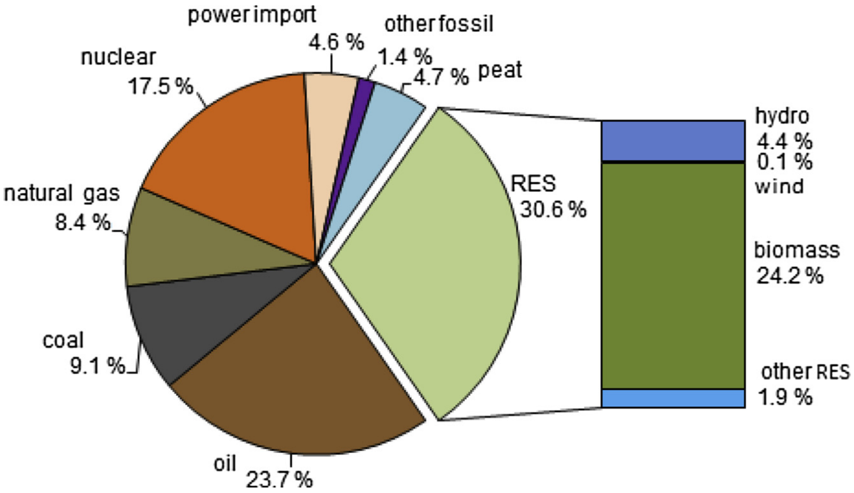

Fig. 2. Share of different sources in primary energy consumption (PEC) in Finland 2012.

methods considering biomass maps and explicit spatial constraints (biometric models) [71]. Considering municipality-level spatial constraints, this potential diminishes further to 14–17 Mm^3 (28–35 TWh) for the whole country [72]. To account for this discrepancy and uncertainty in the literature, we consider two maximum limits of 35 and 51 TWh as potential of forest chips in our analysis, referring to maximum techno-economic potential and maximum techno-ecological potential, respectively, as estimated by Refs. [69,72]. Accordingly, we consider two scenarios for maximum bioenergy potential in Finland, $\text{Maxbio}_{\text{low}}$ and $\text{Maxbio}_{\text{high}}$. Hence, $\text{Maxbio}_{\text{low}}$ accounts for techno-economic potential that can be exploited in the near future, and $\text{Maxbio}_{\text{high}}$, which is more ambitious, for techno-ecological potential that may not be fully economic in the near future under current supportive measures.

Increasing the share of biofuels in transportation by 15% (equal to 7 TWh) is the second major target in Finland's RES plans [64]. Heinimö et al. predicts an increase of 11 TWh in biofuel production capacity by 2020, in addition to today's 5.7 TWh level [73]. This level is even higher than 2020's targets and partially depends on the availability of excess round woods due to the deterioration of pulp and paper industry. The planned biofuel production plants are mainly based on second-generation routes – gasification and Fischer–Tropsch synthesis, and fast pyrolysis – demanding a significant amount of woody biomass [74]. Therefore, a fraction of previously estimated potentials for forest biomass should be allocated to biofuel production in the future. In $\text{Maxbio}_{\text{high}}$, we assume that all the planned capacity is realized and the required woody biomass (11 TWh) is subtracted from total potential (51 TWh). The same analogy is applied to $\text{Maxbio}_{\text{low}}$, resulting in an additional 8 TWh of woody biomass to the current 5.7 TWh production of biofuel. It is assumed that wood imports can compensate the resource losses due to the inefficiencies of biofuel production routes. We do not consider a major share for wood imports in bioenergy use separately, as they do not contribute in national energy security either.

Biogas from municipal biowaste and agro-biomass is the other source of energy examined in this Section. Finland's RES target for 2020 allocates a marginal growth for biogas corresponding to 1 TWh. Höhn et al. (MTT Agrifood Research Finland) [75], has assessed the maximum potential of biogas in three municipality regions in south of Finland: Turku, Salo, and Kymenlaakso. They have considered biomethane production from municipal waste, agricultural residues and dedicated crops, manure, and sludge. With optimized production in 42 biogas plants with less than 10 km distance from feedstock, they conclude a 68% harvest on average, from the maximum theoretical potential of 2.8 TWh/a. Peura and Hyttinen [76] estimates biogas potential for South Ostrobothnia region in the range of 0.6 TWh/a. If these results would be generalized for the whole country, based on population density, the maximum potential reaches approximately 15 TWh/a. Other studies [77,78] have estimated this potential in the range of 15–31 TWh/a, which seems to be more ambitious. After all, we assumed a maximum potential of 15 TWh in $\text{Maxbio}_{\text{high}}$ scenario, while 5 TWh in $\text{Maxbio}_{\text{low}}$ scenario (5 times higher compared to 2020's target) for biogas and agro-biomass potential. For other sources of bioenergy, a consistent potential with 2020's target is deemed or a moderate growth is assumed, based on [73,79–82].

Table 3 summarizes the technical potential of bioenergy for two scenarios of this study, compared to 2012's levels and 2020's targets. The realization of these targets depends on carbon prices, fossil fuel prices, stumpage and chip prices, appropriate forecasting, and subsidies for the use of forest chips in small-scale CHP plants [83,84]. However, it is assumed that the mentioned requirements are fulfilled to monitor the techno-economic consequences of the integration of such scenarios in the Finnish energy system. The biofuel figures presented in Table 3 only reflect the share of biofuels (mainly second-generation biodiesel) which replaces domestic transport needs. In other words, the export of biofuels to other countries and the associated revenues are not considered in this study, neither the import of raw material for second-generation biofuel production. We assume that the ratio of domestic biofuel

Table 3
Current bioenergy use and 2020 targets compared to two maximum bioenergy scenarios defined in this study ($\text{Maxbio}_{\text{low}}$ is techno-economic while $\text{Maxbio}_{\text{high}}$ is techno-ecological in 2014).

Biomass source (TWh/a)	2012	2020 target	$\text{Maxbio}_{\text{low}}$	$\text{Maxbio}_{\text{high}}$
Black liquor	38	38	38	38
Wood industry's by-products and residues	19	19	19	19
Forest chips (only for heat and power)	17	27	27	40
Firewood	12	12	12	12
Biogas[a] and agro-biomass	0.5	1	5	15
Wood pellets	1.8	2	3	4
Biomass-based recycled fuels	1.7	2	3	4
Biofuels[b,c]	2.5	7	8.3	11
Total bioenergy (TWh/a)	92	108	115	143

[a] From sludge, manure, municipal and industrial biowaste.
[b] Woody biomass for second-generation biofuel production is included.
[c] Only share in domestic usage (total production was 5.6 TWh/a in 2012 [73]).

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usage to total biofuel production will increase from 45% in 2012 to 55% and 65% in $\text{Maxbio}_{\text{low}}$ and $\text{Maxbio}_{\text{high}}$ scenarios, respectively.

3.2.2. *Hydropower*

There are approximately 200 hydropower plants in Finland, including run-of-the-river plants with limited reserve capacity. Hydropower capacity is rather fully exploited in Finland or potential sites are under environmental protection [85]. The level of water resources is one of the key factors in Nordic electricity market prices, varying significantly year to year in Finland [86]. While there is no projection for major changes in hydropower capacity in Finland, less stringent environmental legislation for small hydro plants can promote them in the future [87]. Finnish Energy Industries realizes a techno-economic hydropower potential of approximately 940 MW, of which 460 MW stays in protected areas (Ounasjoki and middle-course of Iijoki). Based on current estimations (e.g. by Motiva [88]), we assume an extra hydro potential of 500–600 MW to account for future installations and/or upgrades in the existing fleet.

3.2.3. *Solar energy*

Solar energy has not been harnessed in large scales in Finland. Opposite to general perceptions, the annual potential of solar thermal in Finland is only 20% lower than North Italy. However, since the production occurs mainly in summertime, when the demand is very low, solar thermal cannot contribute the heating network without long-term heat storage systems. Based on Pöyry [89], the potential of solar thermal in Finland is 100 GWh/a for small solar collectors, while 300 GWh/a for large collectors by 2020. IEA Solar Heating and Cooling Program estimated the techno-economic potential of different applications of solar thermal in the range of 1500 GWh/a for Finland, requiring 3.8 million m^2 of collector area [90]. The levelized cost of solar heat production is 120–150 €/MWh, which is higher than the average price of heat from DH (55 €/MWh), yet cheaper than DH price in some areas [89]. In this study, we consider the highest reported potential of 1500 GWh/a for solar heating in Finland.

Solar PV is in different position, as it may contribute in electricity supply in long summer days, where electricity from CHP plants has dramatically inclined. Helsingin Energia, the utility company in Helsinki, is to build the country's largest solar power plant with 340 kWp capacity in Suvilahti by spring 2015 [91]. The project cost is estimated 0.6 M€, implying a levelized cost of 1.8 €/W_p for solar PV plants in this scale. The cost of small-scale solar PV installations at household level is however around 2.7 €/kW_p [92]. The other large solar power plant is to be built at Lappeenranta University of Technology, LUT, with 220 kW capacity [93]. A study by VTT [94] has estimated the country's maximum potential of solar PV up to 3 TWh/a, by assuming 60% roof coverage of all residential buildings in Finland facing south or near (33.7 km^2 in total). In the solar scenario of this study, we consider this 3 TWh/a as the indicative maximum potential for solar PV in Finland.

We assume that the potential in other buildings, other surfaces and walls, and free land areas even out the infeasibility of installing solar panels on the roof of all the residential buildings. Nevertheless, we examine the cases with higher solar PV production to monitor the techno-economic implications.

3.2.4. *Wind energy*

Finland had 260 MW installed wind capacity by 2012, with the average capacity factor of 24% [95]. Wind power is one of the pillars of future RES targets in Finland, with planned production of 6 TWh/a by 2025 (9 TWh/a by 2030) [96]. In assessment of maximum potential of wind, different criteria should be considered, from land use requirement to wind availability. Since wind power is in its formative stages in Finland, yet the maximum potential of resources is not systematically determined. Considering a recent wind farm project with 21 turbines in an area of 31 km^2 [97], one can estimate an average land requirement of 1.5 km^2 per turbine and 75 ha/MW (each turbine 2 MW). This value is relatively higher than as for the US with an average of 35 ha/MW [98], and Denmark and Germany with 17 and 11 ha/MW, respectively [99]. Considering turbines with 2 MW capacity on average, one may calculate the direct land requirement of 2250 km^2 for Finland's 3000 MW planed wind capacity. This comprises less than 1% of the total surface area of the country. If wind turbines would be installed in a more scattered and individual pattern, this land requirement may even expand. Yet the land can be used for other purposes, e.g. farming, but other environmental, landscape, and visual requirements should not be neglected. In the absence of a systematic research, we do not virtually assume a maximum potential for wind resources in Finland. However, it should be noted that 20 GW wind installations might occupy roughly 10% of the country's onshore and offshore surface area. Wind availability and techno-economic feasibility of such installations will definitely limit the maximum resource potential.

4. Results and discussion

4.1. *Technical and economic optimization*

An energy system can be optimized based on different parameters, including minimum costs, minimum emissions, maximum local production, or maximum supply of RES, among others [100]. This study seeks to investigate the maximum RES that can be technically integrated without structural changes in the existing energy system. In addition to the resource availability of RES, the energy system in question should be capable to integrate such resources. The technical capability is related to the flexibility of the energy system in integrating fluctuating RES by the aid of different solutions in the power system, heat network, transport sector, and also energy conversion between different sectors. In this section, this technical flexibility is examined with respect to economic implications for each RES.

4.2. *Integration of bioenergy*

We projected four major changes in biomass sources for the future of Finland, increase in the use of forest chips, biogas, agricultural biomass, and 2nd generation biofuels. Forest chips can be utilized in heat and power production through direct combustion (in fluidized bed replacing peat), cofiring with coal (pellets), replacing coal (torrefaction), pyrolysis oil (replacing oil), and gasification (replacing natural gas). The techno-economic characteristics (e.g. efficiency and investment cost) of each path are defined in the model. Though each path has different environmental impacts and GHG (greenhouse gases) [74], we only consider the CO_2 emissions of the comminuted biomass. Biogas was considered as an alternative for natural gas (considering upgrade inefficiencies) and liquid biofuels for transport sector.

The results of simulation indicate that Finnish energy system can integrate the projected biomass potential, if some technical supports applied. For example, the share of liquid biofuels in domestic transportation may reach 15–18% to achieve the planned targets. If Finland exploits all the realized potential of biomass, the share of bioenergy in PEC will increase to 31 and 37%, for two examined bioenergy scenarios. Fig. 3 illustrates the changes in the share of RES in Finnish energy system, under examined bioenergy scenarios. It is evident that the bioenergy-based scenarios cannot concurrently increase the share of RES-E (33% RES-E in 2012 and 38% in $\text{Maxbio}_{\text{high}}$). The carbon emissions will decline from 47 Mt in 2012 to 35–41 Mt by mobilizing the country's bioenergy potential.

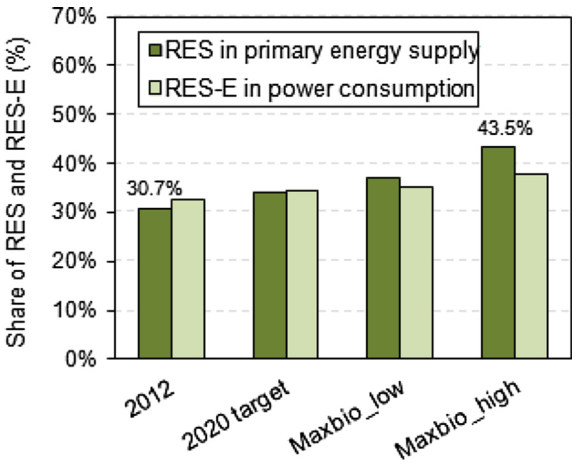

Fig. 3. Share of RES in primary energy and share of RES-E in gross electricity consumption under maximum bioenergy scenarios (assuming fixed energy and power demand of 380 TWh/a and 85 TWh/a, respectively).

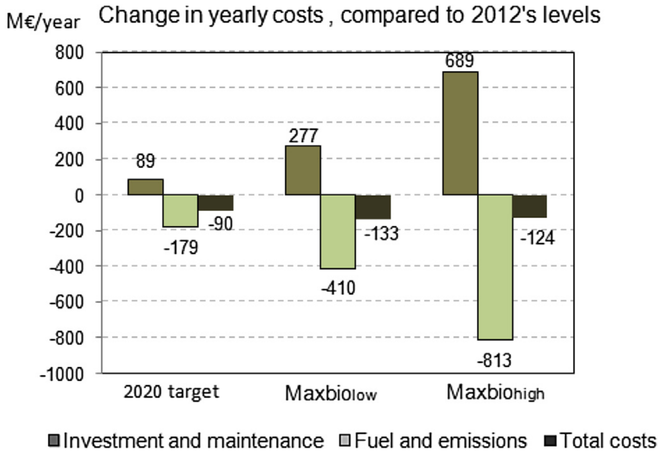

Fig. 4. Indicative changes in the costs of Finnish energy system for bioenergy scenarios, compared to 2012.

From economic perspective, the mobilization of bioenergy potential requires capital investments while partially eliminates fossil fuel imports and associated emission costs. According to the results, the yearly costs of the Finnish energy system reduces by 90 M€/a by realizing 2020's target, and will continue improving to 133 M€/a, in low bioenergy scenario.[4] However, the cost savings in high bioenergy scenario is lower, mainly due to more investments needed to exploit the remaining potential (e.g. by adding more gasification and biogas plants). Though these values are indicative, it postulates that even under current prices of emissions and fuels, mobilization of bioenergy potential offers cost savings, from energy system viewpoint. In Fig. 4, the yearly cost of the Finnish energy system under bioenergy scenarios are compared with 2012's.

4.3. *Integration of hydropower*

Adding the additional 500 MW capacity to the existing hydropower fleet, will boost the share of RES-E in power consumption to 37%, from 33% in 2012. The net power imports inclines by 10% to approximately 16 TWh/a, and the share of RES in PEC improves by 1%-point to 31.5%. No major technical changes are required and the economy of the Finnish energy system improves by cutting 187 M€/a, compared to 2012's.

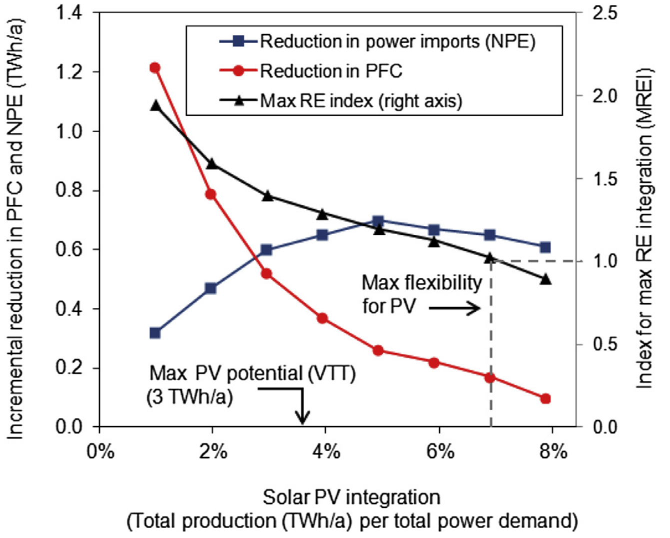

Fig. 5. Solar PV integration (annual production per total demand of 85 TWh/a) and reduction in primary fuel consumption (PFC) and power imports (left axis), versus the max renewable energy integration index (MREI) (right axis).

4.4. *Integration of variable RES*

In this Section, the share of variable RES technologies will be incrementally increased in the energy system. The system reacts on the variations based on the methodology described in Section 2 and the maximum limit is explored employing the indicator introduced in this study (MREI).

Based on the Finnish national TSO (Fingrid), the power system has 200–400 MW capacity for flexible demand in Elspot market (day-ahead power market), by the end of 2012 [113]. We consider different flexibility measures in periods of excess power production by variable RES in the following order. First, 400 MW flexible demand with time scale of maximum 24 h is activated. Then, export capacity of 2500 MW to the external power market until the bottleneck will be in use, if and only if the marginal cost of power production at those periods of power oversupply would be lower in Finland price area, compared to the other Nordics (based on 2012's price variations). Next, an additional 200 MW on-call capacity of electric boilers plus 33 MWe large-scale HP (Katri vala plant) is online, to convert power to heat. Finally, power production in CHP plants is regulated (reduced) and heat-only boilers are put into operation for meeting the corresponding heat demand. The adoption of each measure depends on the time of the year and possible flexibility of the energy system at that particular hour.

4.4.1. *Solar energy integration*

The results illustrate that if the estimated potential of solar heating would be exploited in DH systems with the aid of thermal storage (totally 15 GWh), it covers 3.5% of the DH demand in the country. The share of RES in PEC slightly improves (less than 0.3%-point) by eliminating the use of fuels. From economic viewpoint, this level of solar thermal offers cost savings of 50 M€/a, under 2012's conditions.[5] Approximately 3900 MW$_p$ installed capacity is

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[4] The costs are calculated in 2012-€ with 5% interest rate and carbon cost of 8 €/tonne (see Appendix A for cost of fuels and technologies).

[5] Investment costs of solar thermal based on [101,102], lifetime 25 years, interest rate 5%.

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required to capture the maximum potential of PV estimated by VTT. This was based on the estimation of annual solar power production in Tampere[6] (774 kWh/kW$_p$), which is slightly lower than the estimation of LUT (800 kWh/kW$_p$), yet higher than country's real production data (average 690 kWh/kW$_p$ [4]). Under VTT's maximum PV potential, Finland may cut the power imports by 11%, increasing the share of RES-E in domestic power consumption to 37% (compared to 33% in 2012). No major technical problem occurs, even in sunny summer days with the highest harvest of solar. Realizing this solar PV potential raises the total costs of the Finnish energy system by 560 M€/a, however, compared to 2012 (186 € for each MWh of solar PV production).

We examined solar PV capacities beyond this maximum potential to monitor the effects on the energy system. Based on the results, solar PV could be technically integrated in the system up to 5.6 TWh/a (MREI = 1 at this level), implying that energy system has higher flexibility than realized resources for solar PV. However, this integration level imposes 1090 M€/a additional costs to the system (194 € for each MWh electricity of PV), and demands 67 km^2 surface area. The changes in attained benefits (reduction in power imports and fuel consumption) compared to MREI index in different solar PV integrations are illustrated in Fig. 5.

4.4.2. Wind integration

To model and simulate large-scale wind integrations,[7] upscaling and approximation techniques should be applied. To study the effect of hourly fluctuations in large scale wind integrations, the smoothing effect is calculated based on the ratio of installed wind capacity at any future level to the reference system (260 MW at the end of 2012) [104]. Different studies show that aggregated and dispersed wind production over a large area will experience less periods of peak, calm, and large variations in very small time lags (see Refs. [105–107] for more details). We applied this phenomenon by correcting the annual duration curve of wind production for any desirable installed capacity in the future, compared to the actual data of 2012. Then, the modified annual duration curve is converted back to hourly distributions to represent the hourly variations. The methodology is more explicitly explained in Ref. [108], resulting in generation of more moderate hourly fluctuations in the whole country for high-level wind integrations. Based on [95], the average CF (capacity factor) of 24% is considered for onshore wind in Finland. For offshore wind, capacity factor is estimated as 26% based on the difference in wind speed on the coastal areas in west and south compared to offshore locations, by examining 10 different exemplary locations using online data from Finland's Wind Atlas [109]. We considered a share of 10% wind production from offshore sites for the future installations. The cost of imbalance entailed by wind into the power system, amounting 3–4 €/MWh of wind production [110,111], was also considered in addition to investment costs of 1.5–2 M€/MW [55,112].

Considering the flexibility measures mentioned in the beginning of Section 4.4, the results of our analysis show that Finnish energy system can integrate wind maximum by 18.5–19% of domestic power demand in 2012. At this integration level (15.8–16.2 TWh/a), the sum of benefits attained by wind (reduction in PFC and reduction in power imports) approaches the net change in wind production, resulting in MREI = 1 (see Eq. (1)). This phenomenon is depicted in Fig. 6 for different wind integration levels (each step equals to 1000 MW installation or 2.25 TWh/a production). As it evidences, installing 1000 MW wind in the beginning reduces fuel consumption and power imports by 2.6 and 0.85 TWh/a, respectively, totaling 3.45 TWh/a. The total benefits sinks as the installed wind capacity grow, so that between 7400 and 7600 MW installations the sum of benefits by wind is equal to the total production of wind (including unused excess wind production).

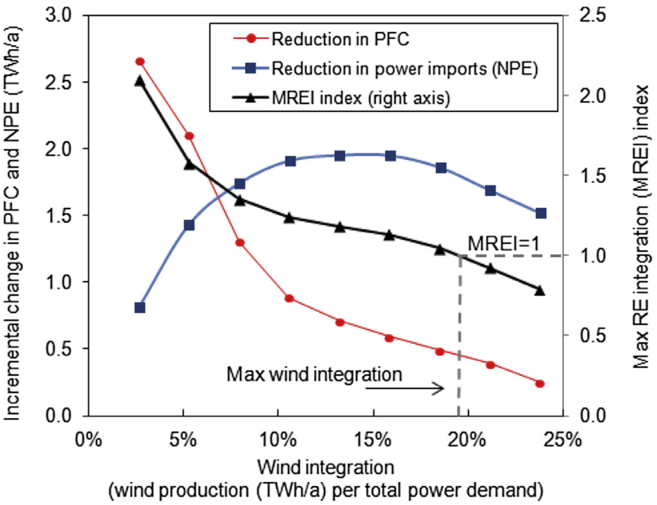

Fig. 6. Maximum level of wind integration into Finland's energy system and the changes in reduction of primary fuel consumption (PFC) and net power exchange (NPE) after each wind integration level (based on total power demand of 85 TWh/a).

This is the point that MREI is 1 and further wind installations do not bring equivalent benefits to the system (see Eq. (1)). The more detailed figures are provided in Appendix B. Based on our analysis, in wind integration of approximately 17.5%, Finnish power system encounters with a challenge of curtailing more than 100 MW oversupply in almost 90 h of the year. In 19% wind integration, the number of hours with more than 100 MW oversupply will reach to 160 h per year (from which around 60 h with more than 300 MW oversupply). To evaluate better, the wind curtailment at this point (MREI = 1) is equal to 2–3% of total yearly wind production.

These results imply that wind integration targets by Finland's Energy Policy are yet in the feasible limit. In maximum wind integration, RES will be approximately 34.6% of PEC, while RES-E will be 57% of domestic power consumption.

By integrating the maximum potential of wind power, Finland still remains a net importer of power (5.1 TWh/a), but with 70% reduction compared to 2012. The total costs of the Finnish energy system decline by 94 M€/a in 10% wind integration (economically optimized level). Integrating wind is still beneficial up to 18.7%, but higher integrations will impose additional costs to the system (Fig. 7). This can be attributed to the replacement of CHP production with wind and heat-only boilers. In Fig. 7, the profitability of different levels of wind integration is compared for two different carbon prices, promising more cost savings in higher carbon prices. Other techno-economic impacts of wind on unit commitment and reserve capacity [114–116] are not considered in this analysis, but balancing costs are included based on [117].

4.4.3. Simultaneous integration of wind and solar PV

The simultaneous integration of wind and solar PV is furthermore examined to determine the optimal integration level of each technology if they interfere. In Ref. [118], it is argued that solar PV variations may further intensify the fluctuations caused by wind, resulting in lower wind integration levels. With this in mind, we simulated wind integrations in different solar PV installations up to 4000 MW$_p$. The results reveal that augmenting the share of solar PV

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[6] This was calculated based on the estimation of solar irradiation for panels with tilt of 60°, azimuth angel of 180°, and AC-to-AC derate factor of 0.75 [103].

[7] Wind integration as the ratio of annual wind energy production (TWh/a) to total power demand.

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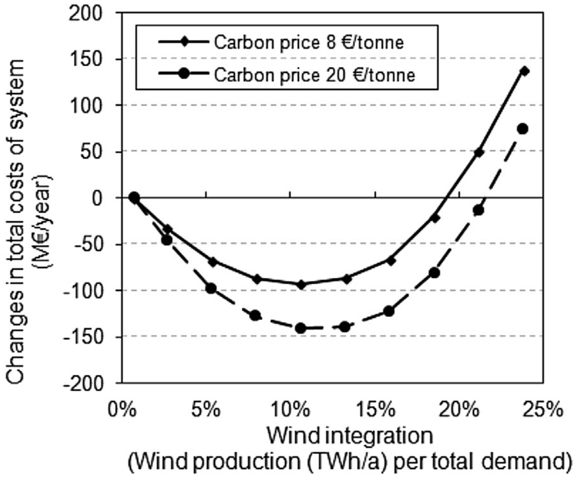

Fig. 7. Profits gained by wind integration for the Finnish energy system compared to 2012 (for carbon emission costs of 8 and 20 €/tonne and interest rate of 5%), negative values indicate reduction in yearly costs.

will constrain the room for higher wind integration. In 4000 MWp installed PV, maximum wind integration shrinks to 16.7% (from 19% for the case without PV). This is due to the fact that wind oversupply occurs mostly at summertime, when the power demand is much lower, concurrent with solar PV peak production. The overall costs of the system increases in higher shares of PV in combination with maximum wind, while the share of RES-E slightly improves.

These changes are depicted in Fig. 8 for different solar PV capacities. As PV installation higher than 1100 MW do not contribute to the share of RES (in combination with maximum wind of 7.3 GW), while increasing the costs of the system, this combination is considered as the most optimal mix of the two technologies.

4.5. Individual HPs (heat pumps)

Individual HPs can increase the share of RES by replacing electric heating. The use of HPs at household level depends on economic attractiveness and incentives, possibility for installation, other alternative heating media (e.g. DH), choice of technology, etc. The impact of HPs on emission reduction compared with other alternatives, like CHP, should be more thoroughly analyzed, as in Ref. [119]. In this study, we assume that HPs could substitute the current electric heating at households, supplying 14 TWh/a heat, in addition to today's utilization of HPs. If HPs could be optimally utilized, this replacement would cut the nation's power consumption by 11%, reducing condensing thermal power and power imports by 66% and 32%, respectively. On the other hand, this reduction in power demand constrains the maximum limit for wind integration, from 19% to 17%. Hence, the maximum possible share of RES-E does not improve proportionally.

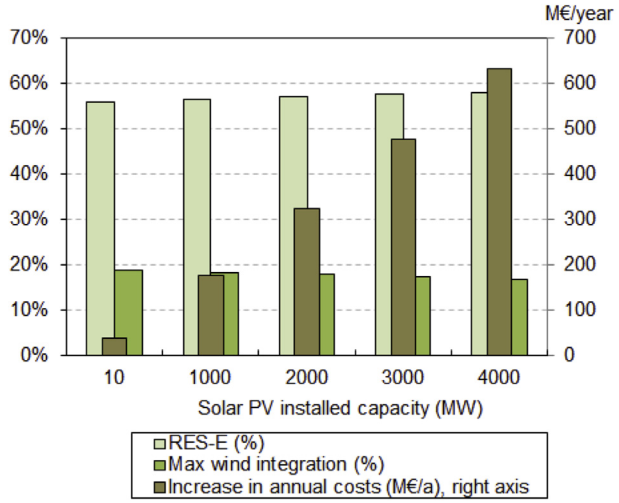

Fig. 8. Combined integration of wind and solar, max wind possible, share of RES-E, and economic impacts.

4.6. Combined renewable energy integration

Finally, a combined scenario is examined to include all the mentioned RES scenarios concurrently. This is to provide a proper answer for the main question: to what extent can Finnish energy system increase the share of RES? The combined scenario is formed based on two different estimations in bioenergy scenarios, resulting in RES_{low} and RES_{high}, respectively. The results indicate that if Finland mobilizes the potentials of bioenergy (as estimated), and integrates solar, hydro, individual HPs, and wind as high as technically possible,[8] the share of RES in PEC totals 44–50% (168–192 TWh/a). The share of RES-E in domestic power consumption will be then 69–71.5%, and the country will be a net power exporter (4–5 TWh/a). Assuming constant nuclear capacity, the share of decarbonized power reaches 93–95%, offering a reduction of 35% in carbon emissions compared to 2012. Fig. 9 depicts the state of Finnish energy system when the highest technical potential of wind, solar, hydro, bioenergy, and individual HPs is exploited, assuming fixed energy demand as today.

The additional costs of the system will boost to 240–250 M€/a with the technology costs considered in this study (see Appendix A), while carbon emissions declines to 32–33 Mt/a. This combined scenario is compared with other scenarios in Table 4.

4.7. Sensitivity of the results to the future changes

This study is to investigate the current potential of Finnish energy system in integrating RES, future changes are briefly reviewed though. Change in energy demand is one of the parameters that may affect the results. Opposite to the prior predictions [120,121], the energy demand shows no significant growth in recent years. The adoption of energy efficiency measures in lighting [122], residential sector [123], and industrial processes [124] may partially compensate or balance out the possible growth in energy demand in the future. A new nuclear power plant (Olkiluoto 3) with 1600 MW capacity is planned to start to operate in 2018[9] [125]. The results of this study might be still valid if the growth in power demand and electrification of other sectors, like transport, would be equal to the additional power supplied by Olkiluoto 3. In Ref. [61], the status of Finnish energy system after Olkiluoto 3 is examined in details. The results demonstrate that the operation of Olkiluoto 3 will diminish the actual share of RES in PEC by 3%-point and the share of RES-E in domestic power use by 5%-point.

Based on our analysis, the maximum potential of RES in PEC will decline to 41–47%, after Olkiluoto 3, compared to the examined combined RES scenarios (Section 4.6). In addition to the increase in the volume of PEC (uranium as fuel), this is also due to the constraints that increased nuclear capacity as a rigid baseload puts on fluctuating wind. Hence, the maximum potential of wind production deteriorates to around 13 TWh/a (cf. 16 TWh/a without

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[8] This is in wind installations of 7300 MW, hydro 3050 MW, solar PV 1100 MW, solar thermal 1.5 TWh/a, and 18 TWh/a heat from individual HPs.

[9] There have been some debates about the opening date or final capacity, but we consider the official announcements.

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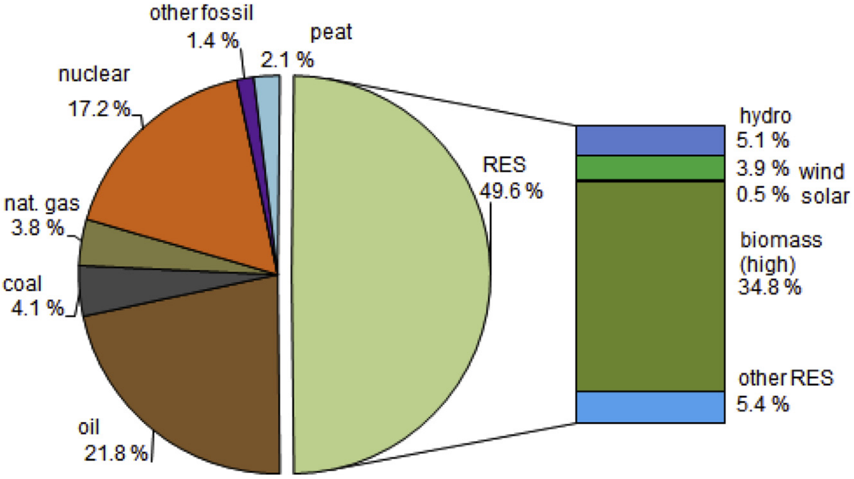

Fig. 9. Finland's total primary energy consumption (PEC) mix in maximum RES integration scenario, domestic energy demand 378.5 TWh/a and net power export 4.5 TWh/a. (for bioenergy sector, the high bioenergy scenario is considered).

Olkiluoto 3). The economic feasibility of wind integration will be constrained by Olkiluoto 3 so that any wind penetration level will increase the system's total costs under fixed power demand as today. In Fig. 10, the impact of Olkiluoto 3 on the Finnish power system is simulated on an hourly basis for two weeks in summer and winter with maximum technical potential of wind and solar PV. In wintertime, the combination of wind-nuclear power meets the demand and extra power can be exported. However, in periods of low power demand, the oversupplied power from variable RES-E exceeds the demand and interconnection capacity, under today's conditions. It should be noted the hydropower plants shown in the Fig. 10 are only run-of-the-river plants, which is estimated to be 30% of all hydropower in Finland. Considering 4 TWh total reservoir capacity of other hydropower plants, it should be noted that the country is not able to store hydropower for long periods, demanding for other flexibility solutions if nuclear policy is to intersect the high-RES energy scenarios.

4.8. Discussion

Different alternatives can serve as flexibility for further integration of fluctuating RES-E, including energy storage [126], interconnection of heat and power sectors [127], electric vehicles [128], alternative transport fuels [129], new regulation strategies for thermal power plants [14], and the expansion of cross-border power grids [130]. The investment and adoption of any flexibility measure depends on the available infrastructure and future RES scenarios for the system in question. While public attitude towards nuclear energy in Finland is positive [131], resulting in plans for increasing the nuclear capacity, further improvement in the share of RES seems to be more challenging in the future. Hence, a wise energy policy should endeavor to find a compromise between the share of RES, carbon-free energy system relied on nuclear baseload, and secure supply of energy. Other characteristic of Finnish energy system is the high share of efficient CHP plants that play a key role in the deployment of local bioenergy. From this angle, distributed generation and electrification of heat sector might interfere with CHP-DH systems, making the setting more challenging for these centralized systems. Electricity storage systems are not economically attractive based on the current use cases in Finnish power market [132] and their economics is highly uncertain [133]. Therefore, any flexibility solution for enhancing the share of RES calls for a detailed system-based study of consequences in different time scales. The relatively lower integration potential for wind in Finland can be associated to the limited interconnection capacity, compared to Denmark and Germany. Even this capacity is not guaranteed to be fully available for power exports at high wind periods. The status of wind production and power demand in neighboring countries are also influential in the future of RES-based scenarios and power market's functions. The confluence of abovementioned challenges demand a consistent and holistic energy policy to maintain the security of energy supply and increase the share of RES, in a wise and future-oriented manner [134].

Table 4
RES in primary energy consumption (PEC) and RES-E in power consumption in different maximum RES scenarios examined in this study, compared to 2012 and the proposed combined scenario.

	Today (2012)	Scenarios for individual sources of renewable energy[a]					Combined scenario[b]
		Maxbio (high)	Hydro	Solar	Wind	HP	
Key changes compared to 2012	–	See Table 3	Adding 600 MW hydro capacity	Adding 3 TWh/a solar PV and 1.5 TWh/a solar thermal	Adding 7500 MW wind	Adding individual HPs to supply 14 TWh/a heat	The combination of mentioned individual scenarios
RES in PEC	30.7%	43.5%	31.5%	31.8%	34.6 %	31.4%	49.7%
RES-E in gross power consumption	32.6 %	37.7%	37.5 %	37.2 %	56.0%	36.6 %	71.5 %
Change in total costs compared to 2012 (M€/a)	–	−124	−183	+484	+38	+80	+247
Carbon emissions[c] (Mt/a)	49.9	36.2	48.6	48.5	45.5	47.0	32.3

[a] Without considering the impact of other RESs.
[b] Explained in Section 4.6.
[c] The equivalent carbon emission of power imports is also calculated to provide a proper basis for comparison with those scenarios without power imports.

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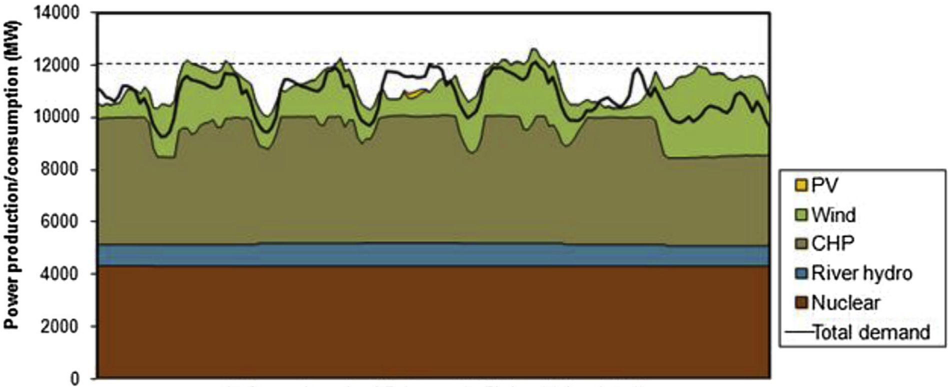
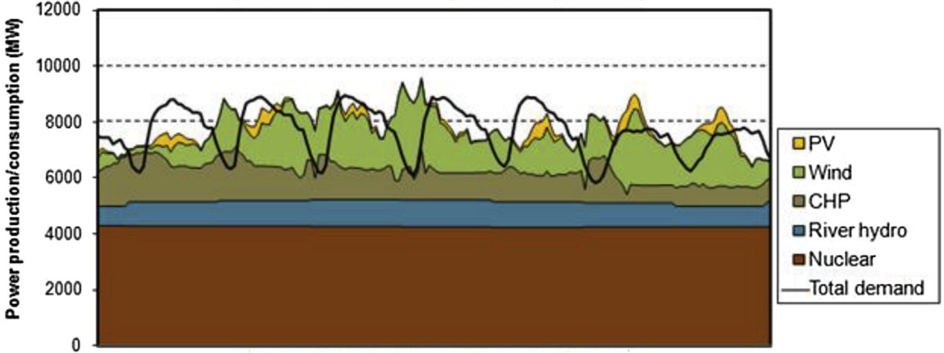


A) Second week of February in Finland (simulated)



B) Second week in August in Finland (simulated)

Fig. 10. Impact of Olkiluoto 3 nuclear power plant on Finnish power system: hourly dispatch of must-run and non-controllable power production compared with total power demand in two weeks in winter (A) and summer (B) under maximum RES examined in this study (fixed demand as 2012). Note: Only run-of-the-river (non-storable) hydropower is illustrated.

5. Concluding remarks

By hourly modeling, the flexibility of Finland's energy system for integration of higher shares of RES was investigated in this study. First, we examined the impact of each technology without considering interference with the other RESs. The results demonstrate that bioenergy will remain the backbone of RES in Finland in the near future, with potentials to maintain 31–37% of PEC (primary energy consumption). Compared to 2020's bioenergy targets, a seven-fold larger capital is required for the mobilization of remaining biomass potential and investment on pretreatment processes and advanced conversion technologies to deliver bioenergy in different carriers (gaseous and liquid fuels). Solar thermal and solar PV can marginally improve the share of RES in PEC, by 0.3% and 1%-point at maximum, respectively. With today's cost of technology and an average yearly production of 780 kWh/kW_p, solar PV imposes additional costs to the energy system at any integration level. It means the reduction in fuel consumption and power imports after solar PV do not balance out the associated investment in Finland's situation. Individual HPs can diminish the nation's power demand by 10% if they could substitute the existing electric heating. They could also level up the share of RES in PEC by 3%-point. However, HPs do not improve the share of RES-E proportionally, as they put constrain on wind integration levels, given a fixed power production capacity from thermal plants as well as constant electricity demand as 2012.

At present, without adopting major flexibility solutions, the maximum potential for wind integration into Finnish energy system is 18.5–19%, a wind production of 15.8–16.2 TWh/a (installed capacity of 7400–7600 MW). This estimation was based on the assumption that Finland can export excess power at periods of wind oversupply by employing the existing interconnection corridors. The most economically beneficial wind production, however, occurs in 10% integration levels (installed capacity of 4000 MW), a result that conforms to the government's wind expansion plans. In higher wind uptake levels, the economic attractiveness deteriorates since CHP plants must be partially replaced with heat-only and electric boilers to avert power overproduction. The share of wind will diminish if solar PV would be significantly penetrated, as wind oversupply arises mostly at summertime when solar production experiences peaks, and heat and power demand are in minimum levels.

In the most optimized cases, Finland can increase the share of RES in PEC by 44–50% in the current energy system (depending on bioenergy production). The share of RES in domestic power production can reach maximum to 69–71.5%, making Finland a net power exporter after harnessing all the technical potential of RESs. Nevertheless, the operation of the coming nuclear power plant (Olkiluoto 3) will diminish the share of RES and RES-E, by 3 and 5%-point, respectively. This is mainly based on the dramatic growth of nuclear fuel in PEC and interference with possible high wind levels: Olkiluoto 3 deteriorates the potential of wind integration by 21%. However, after resignation of a share of thermal plants or increase in the power demand, the setting may favor the operation of Olkiluoto 3, in terms of economics and decarbonization (emission reduction).

The results of this study demonstrate the significance of system-based (including heat, power, and transport sector) approaches with adequately small time resolutions in dealing with RES scenarios. Without major flexibility measures, Finnish energy system may not be able to easily integrate RES in shares higher than 50% in PEC. Any future energy policy and energy planning should rigorously reflect this feasible potential and/or investigate the most suitable measures for harvesting more RESs. In the future work, the authors will focus on the most optimal solutions for increasing the share of RES in Finland, based on electrification of heat sector and energy storage, for example. The results of this study can be improved by adopting more realistic strategies for the operation and decommissioning of thermal power plants, inclusion of power exchange in multiple electricity corridors, and more sophisticated methods in modeling of PV production. Moreover, detailed study of (backup) thermal power plants under ramping conditions will correct the overestimation of profitability of variable RES scenarios. In this study, the potential for hydropower, bioenergy, solar thermal and solar PV, HPs, and wind energy was examined as RESs. Other types of RES (e.g. tidal energy, geothermal energy, wave energy, etc.) may increase the maximum potential but requires more detailed resource assessment and integration studies.

Acknowledgments

The authors appreciate the funds and supports provided by Aalto University's Energy Efficiency research program, Aalto ENG Doctoral School, and STEEM project (Sustainable Transition of European Energy Markets). We also thank Department of Development and Planning, Aalborg University, Denmark, for providing EnergyPLAN tool and the associated documentation publicly available for the research community.

Appendix

A. Input data

Table A.1
Costs and lifetime of different technologies used in this study based on [54–57], otherwise mentioned.

Cost of different technologies	Unit	Cost per unit	Lifetime	Fixed O&M costs	Note
		Million euro	year	% of installation costs	
Hydropower plant	MW_e	1.5	50	0.5	
Condensing power plant	MW_e	1.3	35	4	An approximated average for coal, gas and biomass plants
Nuclear power plant	MW_e	4	50	1	
Wind (onshore)	MW_e	1.45	25	2.7	
Wind (offshore)	MW_e	1.95	30	3	
Heat-only boilers	MW_{th}	0.13	40	0.5	Mainly oil and gas plants
Small- and medium-scale CHP unit	MW_e	0.9	20	5	
Large CHP plant	MW_e	1.3	35	3.5	
Large-scale heat pump	MW_e	0.6	30	1	
Solar thermal	GWh/a	0.4	20	0.1	With considering
Thermal storage	GWh	0.9	25	1	
Biogas plants	GWh/a	0.35	30	1	
Gasification plant	MW_e	0.5	20	5	With considering [135]
Biodiesel plant	$MW_{biomass}$	0.3	20	3	With considering [136]
Households level and small-scale distributed generation					
Solar PV	MW_e	2.7	20	0.1	With considering [92]
Boiler	MW_{th}	0.2	20	1	
Electric boiler	MW_e	0.4	25	0.1	
Heat pump	MW_e	7	15	1	

Table A.2
Fuel costs (excluding taxes) for the reference scenario based on [59,137].

Fuel and emission costs	Unit	Cost per unit (€)	Note
Coal	GJ	3.9	Simulated and input together with peat based on their reported shares (6.9 €/GJ for heat production)
Peat	GJ	4.2	
Natural gas	GJ	10.3	(13.05 €/Gj in heat production)
Fuel oil	GJ	12.8	Average of heavy and light oil
Diesel	GJ	16.4	
Forest wood chips	GJ	5.5	Based on the mixed used in this study (dry biomass)
Wood pellets	GJ	12.5	

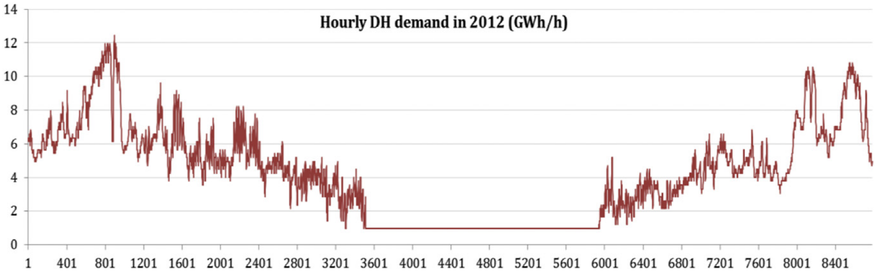


Fig. A.1. Modeling hourly DH demand for the whole country in 2012.

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B. Wind integration

Table B.1
Technical implications of wind integration into the Finnish energy system from 1 GW to 8 GW capacities

	Unit	Further wind installations (MW)							
		1000	2000	3000	4000	5000	6000	7000	8000
Annual wind production	TWh/a	2.3	4.5	6.7	9.0	11.2	13.5	15.7	18.0
Wind integration [a]	–	2.6%	5.3%	7.9%	10.6%	13.2%	15.8%	18.5%	21.1%
Incremental reduction in primary energy consumption [b] (PEC)	TWh/a	0.5	−0.1	−0.9	−1.4	−1.5	−1.7	−1.8	−1.9
Critical excess power production [c] (CEEP)	TWh/a	0.00	0.00	0.00	0.00	0.00	0.01	0.09	0.31
Incremental reduction in primary fuel consumption [d](PFC)	TWh/a	2.66	2.10	1.30	0.88	0.71	0.59	0.49	0.39
Incremental reduction in net power imports	TWh/a	0.81	1.43	1.74	1.91	1.95	1.95	1.86	1.69
Total benefits to the energy system [e]	TWh/a	3.47	3.53	3.04	2.79	2.66	2.54	2.35	2.08
Max RE integration (MREI) index [f]	–	2.10	1.58	1.35	1.24	1.18	1.13	1.04	0.92

[a] Total wind production per total power demand (TWh/a).

[b] Including power imports and wind itself.

[c] The yearly amount of excess power that cannot be used or converted to other energy carriers.

[d] Primary fuel include all the fossil fuels and biomass, but not secondary fuels like synthesized hydrogen.

[e] Sum of the two previous rows in this Table, See Eq. (1).

[f] Where the MREI declines under 1, the sum of benefits are lower than incremental wind production (see Eq. (1)). Here, the max wind integration is calculated as 7500–7700 MW.

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Please cite this article in press as: Zakeri B, et al., Higher renewable energy integration into the existing energy system of Finland – Is there any maximum limit?, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.01.007

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